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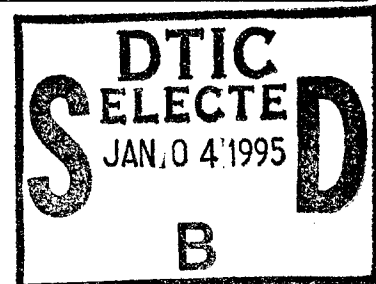Construction Engineering
Research Laboratories

CEPLOAD: A Load-Allocation Program for Army Central Energy Plants

by
Chris Dilks, Ralph Moshage, John A. Kinast, Richard Biederman, Christopher F. Blazek

Significant energy savings may be achieved through improved coordination of boiler operation in Army central energy plants. Historically, plant operators have tended to run their facilities conservatively to cover the uncertainty of imminent loads while ensuring the reliability of the plant. Because a properly adjusted boiler's operating efficiency depends primarily on its current load, and because most boilers produce their peak efficiencies in the range of 80 percent to 100 percent of their rated capacity, a preferred operating method would maintain each boiler's load as close as possible to the point of maximum efficiency. Most Army heating and cooling loads are related to the weather. An accurate forecast of loads into the near future should make it possible to adjust the boilers to handle those loads more efficiently. Given a reliable forecast model for future loads and an evaluation of boiler operating parameters, an optimum boiler load allocation strategy may be developed. Such a strategy could help the Army improve energy efficiency and reduce the operating costs.

The overall objective of this research is to develop a computer-based expert system to help central energy plant personnel optimize boiler operations based on accurate load forecasts. This report documents the development of an accurate load-forecasting model and a prototype expert system called CEPLOAD, which can use the model to help energy plant personnel optimize boiler load allocation.

Boiler Load Allocation Program

195	Last Load, 1000 lb steam/hr
7/19/93	Date of Last Load
11:02:41AM	Time of Last Load
79.88065	Net Eff. %
35	Current Temperature, F

St1 — Boiler 1   Fuel: Gas   Status: ON   Load: 70
St2 — Boiler 2   Fuel: Gas   Status: ON   Load: 79
St3 — Boiler 3   Fuel: Gas   Status: ON   Load: 46
St4 — Boiler 4   Fuel: Gas   Status: OFF   Load: 0

Evaluate | Temp Forecast
Availability | Load Forecast
Forecast Model | Cost Factors
Exit | Boiler Definition

☒ Manual mode

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The overall objective of this research is to develop a computer-based expert system to help central energy plant personnel optimize boiler operations based on accurate load forecasts. This report documents the development of an accurate load-forecasting model and a prototype expert system called CEPLOAD, which can use the model to help energy plant personnel optimize boiler load allocation.

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Foreword

This study was conducted for U.S. Army Center for Public Works (USACPW) under Project 4A162784AT45, "Energy and Energy Conservation"; Work Unit EQ-XK3, "Energy and Energy Conservation." The technical monitor was Dennis Vevang, CECPW-EM.

The work was performed by Energy and Utility Systems Division (FE), Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was Ralph Moshage. A portion of this work was conducted under contract to USACERL by John A. Kinast, Christopher F. Blazek, and Richard Biederman of the Institute of Gas Technology (IGT). Contributions to this report by Frank Johnson, CECER-FEP, and John Spoonamore, Science Department Chairman at Centennial High School, Champaign, IL, are gratefully acknowledged. Donald F. Fournier is Acting Chief, CECER-FE and Dr. David M. Joncich is Acting Chief, CECER-FL. The USACERL technical editor was Gordon L. Cohen, Information Management Office.

LTC David J. Rehbein is Commander and Acting Director, USACERL, and Dr. Michael J. O'Connor is Technical Director.

Contents

List of Figures and Tables

1 Introduction

Background

Significant energy savings may be achieved through improved coordination of boiler operation in Army central heating facilities. Historically, plant operators have tended to run their facilities conservatively to accommodate the uncertainty of imminent loads while ensuring the reliability of the plant. Because a properly adjusted boiler's operating efficiency depends primarily on the load it is experiencing, and because most boilers produce their peak efficiencies in the range of 80 percent to 100 percent of their rated capacity, a preferred operating method would maintain each boiler's load as close as possible to the point of maximum efficiency. The conservative operating approach may have multiple boilers operating when fewer could accommodate the load more efficiently, even if one is set on standby, or "banked."

Most loads experienced by Army central energy plants are heating and cooling loads, which are related to the weather. Therefore, it is possible to forecast the loads that should be experienced within the near future in time to adjust the boilers for those loads. Given a reliable forecast model for future loads and an evaluation of boiler operating parameters, an optimum boiler load allocation strategy may be developed. The Army could improve the efficiency and reduce the operating costs of large central heating facilities at many installations by implementing such a strategy.

Due to the dynamics of the problem, however, and the large number of factors to be considered in a methodology, an automated system for helping plant personnel identify the optimal boiler load allocations is considered essential for implementing the concept.

Objectives

The overall objective of this research is to develop a computer-based expert system to help central energy plant personnel optimize boiler operations based on accurate load forecasts. The objective of this phase of the work was to develop an accurate load-forecasting model and a prototype expert system that can use the model to help energy plant personnel optimize boiler load allocation.

Approach

Historical boiler load and outdoor temperature data from two Army installations were used with commercial forecasting software to develop a load forecasting model. The model was then tested against a different set of historical data to evaluate the model's validity. The validated model was then integrated into a prototype expert system, which was developed using a commercial expert system software shell. A process for optimizing boiler load allocation was also developed and incorporated into the expert system. The working prototype was then documented for future development and enhancement.

Scope

Although the specific results of this project apply to large central heating plants, large chiller plants for district cooling could also be modeled (with their own forecasting algorithms) for more efficient operation.

Mode of Technology Transfer

The prototype expert system will be developed further and refined, then field-tested by energy plant personnel at several demonstration sites. The final product will be transferred to Army users with a software user's guide. The expert system will also be publicized in the *Public Works Digest*. Future enhancements to the expert system may include an interface for importing data from a computerized boiler log program currently being developed by USACERL for the Naval Air Emissions Tracking System (NAETS).

2 Forecast Model Development

Data Considerations

The steam load and temperature data used in this study were derived from two sources: Fort Benjamin Harrison, IN, and Picatinny Arsenal, NJ. The Fort Harrison data were for 1 January 1990 to 19 August 1991. These data series included a number of breaks and discontinuities, so the data series were subdivided into smaller segments of continuous readings. The Fort Harrison data contained information on three steam lines: alpha, beta, and delta. Unfortunately, only the beta line proved useful for forecasting. Alpha and delta steam lines were not considered in the forecast model preparation. (The study in which these data were recorded is documented in the Facilities Engineering Applications Program Technical Report FEAP-TR-FE-93/15, *Steam Dispatching Control System Demonstration at Fort Benjamin Harrison*, by Christopher C. Dilks, Ralph E. Moshage, and Mike C.J. Lin [USACERL, July 1993]).

The Picatinny data were for 1988 and 1989. Steam load information was contained in the log for boilers 4, 5, and 6. However, boiler number 4 produced steam erratically and inconsistently, so forecast models were evaluated using only the steam load information from boilers 5 and 6. Concurrent temperature information was available, but several days of data were missing from the Picatinny files.

The data from each facility were divided into time periods of about 2 months in duration. The length of the time period was selected for three reasons: (1) testing showed that time periods longer than 2 months do not significantly improve model estimation or forecasting accuracy, (2) time periods shorter than 4 weeks may not adequately capture the full range of temperature/load interactions for an entire "weather period," and (3) comparisons of various 2 month periods can provide useful insight into seasonal effects.

Forecast Methodology

The forecast method selected for this application is known as dynamic regression modeling, a multivariate forecasting method that is appropriate when strong explanatory factors (known as *exogenous variables*) are present. Regression analysis

helps the user to understand how one variable (steam load) depends on exogenous variables (e.g., temperature). Another reason for using dynamic regression modeling was its successful application for similar purposes by other investigators (Spoonamore, August 1991; Lin and Carnahan, September 1991).

The only drawback to dynamic regression modeling, is that, because the forecasts are conditioned on unknown exogenous variables (temperature, in this study), a forecast of the exogenous variables must also be made. This study proceeded under the assumption that reliable temperature forecasts can be acquired. Fortunately, this assumption is reasonable because 24- and 48-hour weather forecasts are widely available. Their accuracy, however, will affect the degree of precision achieved by the forecast model.

Dynamic regression models may contain three types of model terms. The first type is independent (explanatory) variables—temperature, in this report—which may be specified as concurrent or lagged variables. The boiler load forecast model may contain an unlagged TEMP variable as well as one or several lags of the temperature variable, denoted as TEMP[-x]. These independent variables and their associated lags are selected for their ability to increase model fit to the historical data and enhance the potential for forecasting accuracy.

Second, dynamic regression models may also contain lagged variables representing previous values of the dependent variable. These optional variables, denoted as FLOW[-x] for current purposes, provide information about the relationship between the dependent variable and itself in previous periods. Models incorporating lagged dependent variable terms may become extremely complex due to phase-interaction effects between lagged dependent variables and lagged independent variables. Another effect that should be noted is that predictions built using a model with lagged dependent variables must use predictions, rather than actual data, to prepare forecasts. For example, a model that contains a dependent variable lagged by six periods will require the use of predicted data if the forecast horizon exceeds six periods. These predictions, however, can be provided by the forecast model.

The third component is the autoregressive error term, an optional component, computes the error between predicted and realized values of the dependent variable in various periods. Autoregressive error terms, also known as Cochrane-Orcutt terms, are always stated with their associated lag. For example, an AUTO[-24] term would cause the model to include the forecast error that occurred 24 periods previously. Significant correlations in the pattern of forecast errors can indicate that the historical data contain information that could be used predicting the future. Autoregressive error terms are often useful for modeling influences that are not sufficiently explained

by independent variables and their lags. However, as strong explanatory variables are added to a given model, the importance of autoregressive error terms should decline. Autoregressive error terms prevent the model from ever straying too far from actual conditions. However, the autoregressive error term is really an error-correction term rather than a variable to measure causality in the data.

3 Development of the Model

Forecasting Boiler Loads

The process of forecasting the boiler load data began with selection of appropriate time periods. This process was directed primarily by the availability of data. As discussed in Chapter 2, data sections were constructed to avoid incomplete steam load or temperature data. These data series could be presented graphically for each time period. Figure 1 presents such a plot for Picatinny Arsenal from 15 October to 15 December 1988. The x-axis presents the time (in hours), the first y-axis presents steam flow (in thousands of pounds per hour), and the second y-axis presents the temperature (in degrees Fahrenheit). A strong negative correlation was observed, as expected, between temperature and steam load for all time periods.

For each time period a basic model was constructed, consisting of an unlagged TEMP variable, a one-period lag of the dependent variable (denoted as FLOW[-1]), and a constant term. These terms were selected because they are highly significant for all time periods. Therefore, these variables explain a large part of the behavior of the steam load data. Working from this base model, additional terms were added sequentially. The percentage of variance in the data that is explained by the regression equation—known as R-squared—was measured after each model term was added, and the T-statistic was computed to test the significance of each variable. Further guidance was given by the BIC statistic, which measures the explanatory power of the regression equation while penalizing model complexity. The BIC statistic is a complex, nonlinear function that is useful only for comparisons of different models. During the modeling process, the addition of certain variables may cause other previously significant variables to lose their significance, causing them to be dropped from the model. This occurrence is typically caused by multicollinearity—several variables attempting to explain the same behavior in the data. In some cases, the addition of autoregressive error terms would radically change the structure of the model, causing several independent variable lags to lose significance. The mix of explanatory and autoregressive error terms proved to be a sensitive parameter during model building. Consequently, constructing the dynamic regression model became a matter of trying many different combinations of variables.
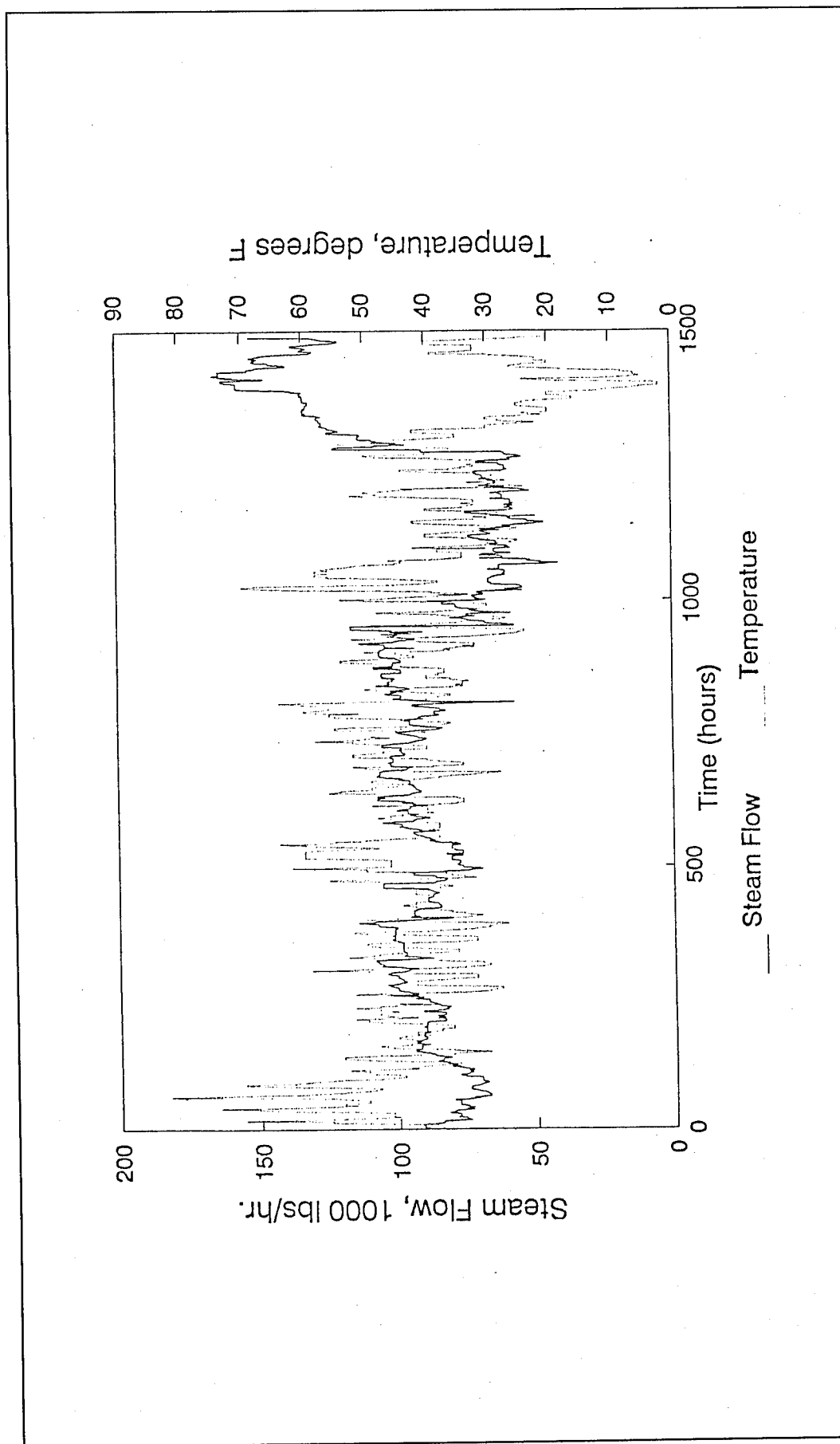
Figure 1.   Sample of steam flow and temperature data for Picatinny.

For each data set, a best-fit model was found. In most cases, differences in the best-fit model were observed between time periods for the same base. However, a common-denominator model was found for each base, i.e., a model that works well for all time periods. The finding of a common-denominator model is important because it indicates that a forecast model can be constructed to serve as an all-season boiler load estimator for a given facility. Another significant finding was that the recommended model specification is significantly different for Picatinny than for Fort Benjamin Harrison. This suggests that a generic boiler load prediction equation for all facilities cannot be found, and that dynamic regression model parameters must be estimated for each facility at which the boiler load allocation expert system is to be used.

Fort Benjamin Harrison

The forecast model for Fort Benjamin Harrison proved the less successful of the two data series. Although an adequate forecast model was constructed, the R-squared value (0.95 to 0.97) and BIC statistic (414 to 606) were significantly inferior to those recorded for the Picatinny model (R-squared value of 0.97 to 0.98 and BIC statistic of 3.35 to 3.13). This relative lack of accuracy may have resulted from the fact that only one of the three steam lines at Fort Harrison was used for forecasting, while the others were ignored (as explained in Chapter 2). Several attempts were made to forecast using an aggregate of the steam lines, but in all cases a better fit to the historical data was achieved using only the beta steam line. Apparently, some valuable steam load/temperature information was obscured as a result of the intermittent operation of the alpha and delta lines. Nevertheless, a dynamic regression model with acceptable fit was produced, and is shown below in Table 1.

Table 1. Recommended dynamic regression equation for Fort Benjamin Harrison.

Variable	Coefficient
TEMP	-112.420498
FLOW[-1]	0.701146
TEMP[-1]	101.263721
FLOW[-2]	0.243519
_AUTO[-24]	0.332310
_CONSTANT	1367.94

NOTE: Coefficients shown in Table 1 reflect model applied to data from time period 16 February–18 March 1991.

The recommended model for Fort Harrison includes an unlagged TEMP independent variable, a one-period lag of the dependent variable, and a one-period lag of the TEMP independent variable. A two-period lag of the dependent variable and a 24-hour lagged autoregressive error term are also included in the model. The dependence of this model on an autoregressive error term suggests that the independent temperature variable is not providing sufficient leading-indicator information. Thus, the model is attempting to compensate by correcting for the previous day's error. Furthermore, additional variable lags were significant for some but not all time

periods. These lags included the 7th lag, 10th lag, and 12th lag. These unusual lags are difficult to understand intuitively, and justification for their inclusion in any model would be difficult. Given the varying significance of additional model terms, it was decided to recommend only the basic model that appears in Table 1. For these reasons, the success of the forecast model was not overwhelming. Given data of better quality, a superior regression model could probably be developed for Fort Harrison.

Picatinny Arsenal

The results of the forecasting effort were much better for Picatinny Arsenal. A dynamic regression model was built that displayed a very high level of fit to historical data and excellent consistency between different time periods. No affinity existed in the model for autoregressive error terms, and very few lags were found to be significant other than the ones specified in the regression equation. This indicates that the independent temperature variable provides sufficient information on which to build forecasts. Table 2 presents the recommended regression equation for Picatinny Arsenal.

This model includes an unlagged TEMP independent variable and a one-period lag of the dependent variable. Four-period lags of the dependent and independent variable are also specified. This model performed very well, producing an R-squared value of 0.97 to 0.98 and a BIC statistic of 3.35 to 3.13. The model is compact and shows great promise for forecasting ability.

Figure 2 shows the forecasting ability of the recommended dynamic regression model for 1 March to 30 April 1988, the time period for which the forecast model was developed. Figure 3 shows the forecasting ability of the same model for a different time period—15 October to 15 December 1988. Figure 3 shows slightly greater forecast error than Figure 2, which is to be expected, but it also shows that the forecast model did an excellent job. Such a comparison was made with a number of other time periods, and the forecast model continued to perform well. Therefore, it can be concluded that the forecast equation is well suited for all-year boiler load prediction at Picatinny Arsenal.

Table 2. Recommended dynamic regression equation for Picatinny Arsenal.

Variable	Coefficient
TEMP	-0.09404
FLOW[-1]	0.913717
FLOW[-4]	0.051614
TEMP[-4]	0.034971
_CONSTANT	6.52

NOTE 1: Coefficients shown in Table 2 reflect model applied to data from time period 1 March–30 April 1988.

NOTE 2: Coefficients of model terms are not directly comparable in the absence of standardized regression coefficients.
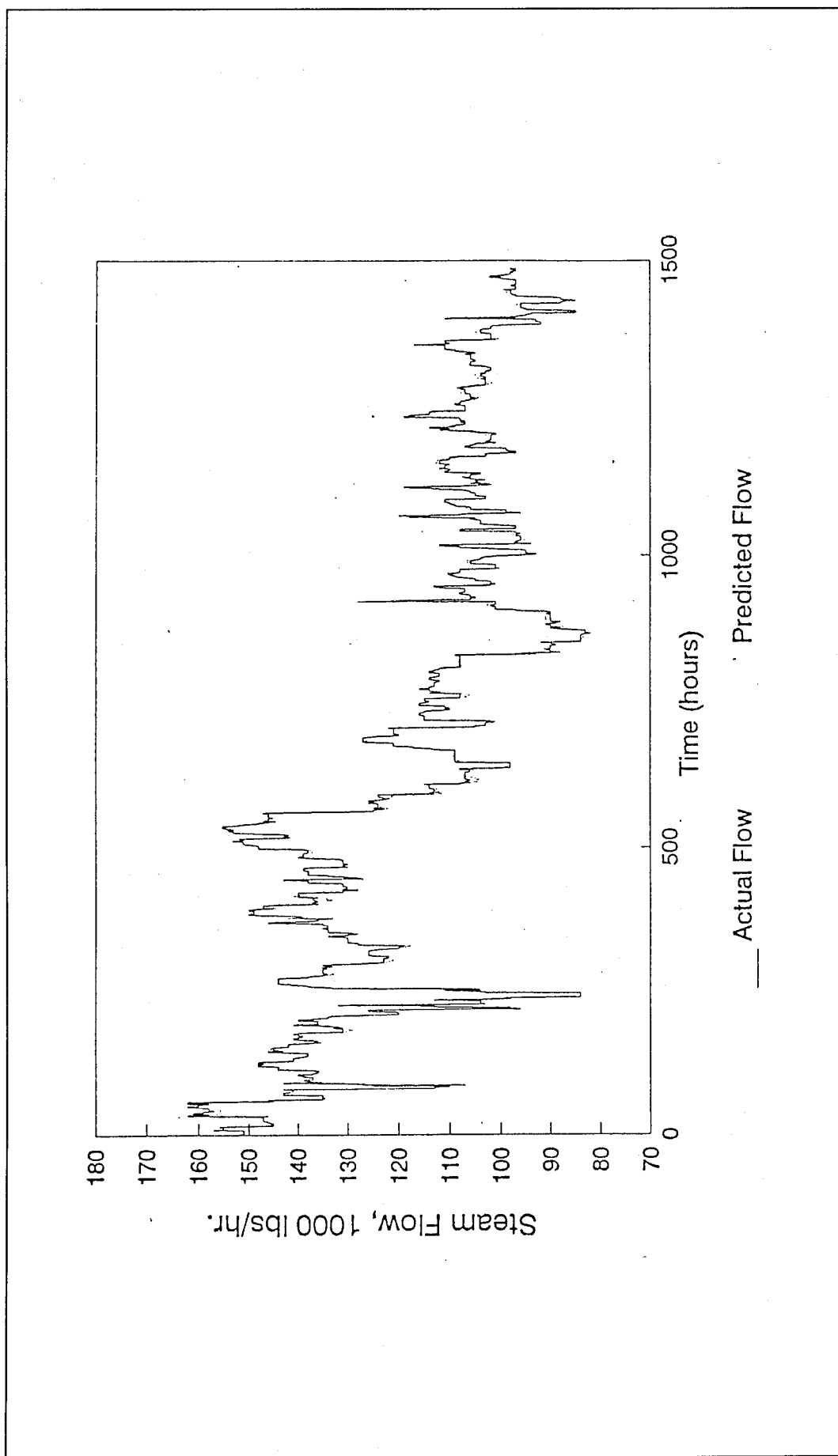
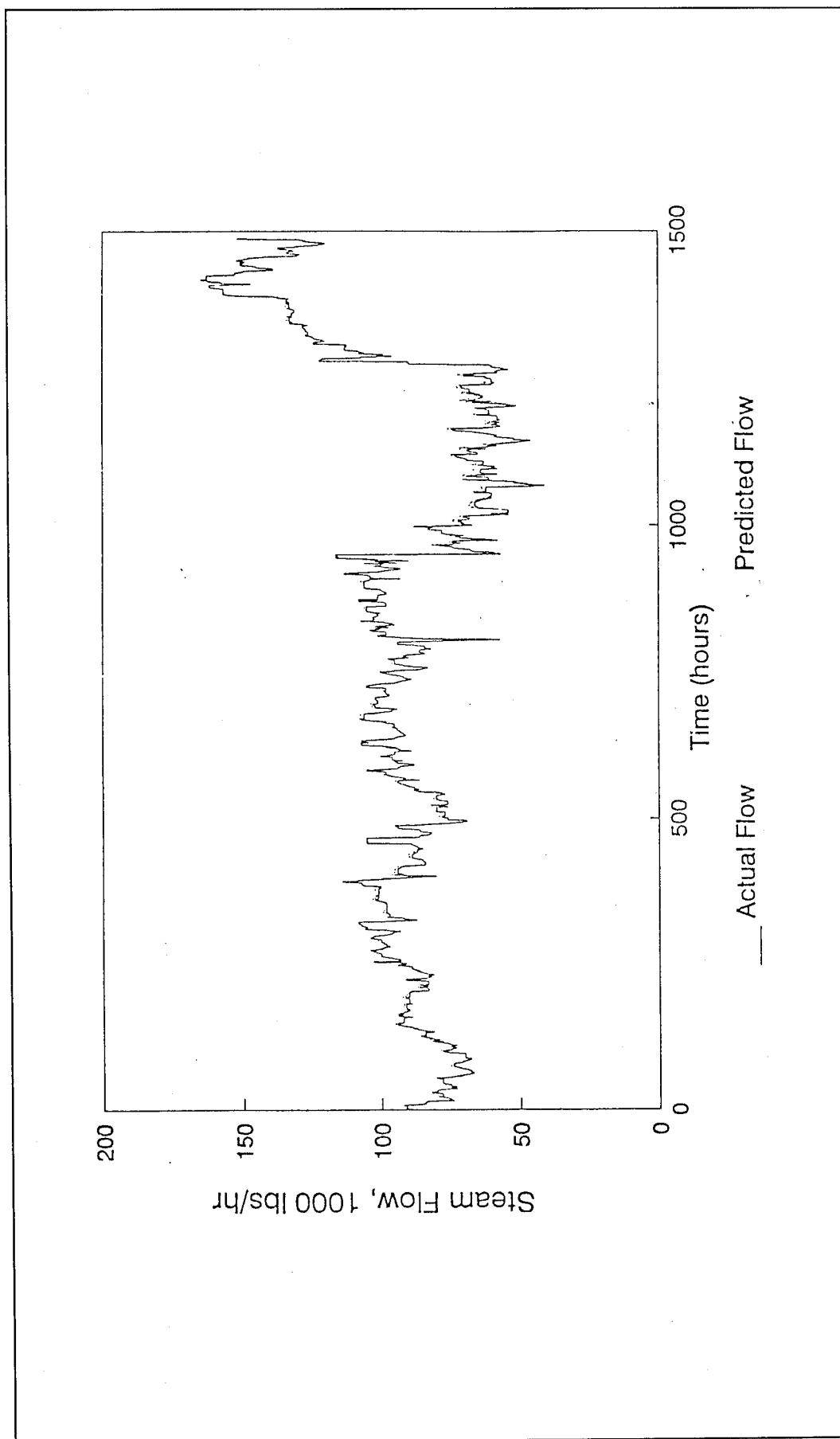**Figure 2. Comparison of predicted flow and actual flow at Picatinny, March–April 1988.**

Figure 3. Comparison of predicted flow with actual flow at Picatinny, 15 October–15 December 1988.

User Input Requirements

As indicated by the structure of the models presented in Tables 1 and 2, the user is required to provide a temperature forecast for a period of time equal to the desired steam load forecast horizon. Thus, for a 24-hour steam load prediction, a 24-hour temperature forecast is required. CEPLOAD, the prototype boiler load allocation expert system, includes a data screen to accept hourly temperature forecast inputs. For the expert system to use the model correctly, the user must input updated temperature forecasts frequently.

One method for inputting the forecast data is for the user to enter 24 hours of temperature forecasts once each day (in addition to actual temperature readings, which should be input every hour). As an option, the user can modify the temperature forecast values at any time to reflect updated information, such as the movement of an unexpected weather front toward the base. However, modifying temperature forecast values may increase the likelihood of sudden changes in the recommendations of the allocation expert system.

Forecast Model Input Facility

A model input facility (input specification form) was developed, which will greatly aid the user in the maintenance of the statistical forecast portion of the boiler load allocation program. This input facility is used to change the model specification (i.e., terms such as lagged dependent and independent variables and autoregressive error terms) or the coefficients of any variables. The input facility is replicated in Table 3.

The input facility can be used to easily update or change the forecast model specification if facility conditions change or the model is applied to a new facility. In general, forecast model development should be viewed as a maintenance function to be performed periodically to ensure that the model retains its validity. The user is strongly cautioned, however, that even small changes to a regression equation can have a dramatic impact on the ability of the model to forecast accurately. Changes to the regression equation should be made only after a comprehensive data analysis. An example of a completed model input specification form for the Picatinny regression equation is provided in Table 4.

Table 3. Dynamic regression model input specification form.

Time Period	Dep.Var. FLOW	Indep.Var. TEMP	Auto Regressive	Constant	Indep.Var WEEKEND
unlagged	-	X	-	X	X
-1	X	X	X	-	X
-2	X	X	X	-	X
-3	X	X	X	-	X
-4	X	X	X	-	X
-6	X	X	X	-	X
-12	X	X	X	-	X
-24	X	X	X	-	X
-48	X	X	X	-	X
-72	X	X	X	-	X
-96	X	X	X	-	X
WHERE: x = possible coefficient					

The "Weekend Effect"

A "weekend effect" may exist for certain installations. Some facilities may experience reduced steam consumption on weekends due to lower activity or personnel levels. This effect was not observed during the modeling process for Fort Benjamin Harrison or Picatinny Arsenal, but the authors believe it may be significant enough at some installations to warrant modification of the forecast methodology. Fortunately, a relatively simple procedure exists for addressing the weekend effect. A dummy variable may be created for Saturday and Sunday observations. A dummy variable takes one of only two possible values: *zero* for nonoccurrences (Monday through Friday), or *one* for occurrences (Saturday and Sunday). To implement this procedure, the user would be required to create a new variable and to code each hourly observation as either 0 or 1, depending on

Table 4. Example model specification form for Picatinny Arsenal model.

Time Period	Dep.Var. FLOW	Indep.Var. TEMP	Auto Regressive	Constant	Indep.Var WEEKEND
unlagged	-	-0.09404	-	6.52	-
-1	0.913717	-	-	-	-
-2	-	-	-	-	-
-3	-	-	-	-	-
-4	0.051614	0.034971	-	-	-

whether the observation took place on a weekday or weekend. The forecast model would then include a variable that would not have any effect during the week, but would influence the steam load prediction on weekends (positively or negatively, depending on the sign of the coefficient). This dummy variable could also be useful for describing other large movements of personnel away from base, such as battalion field exercises or troop excursions. The effect of such temporary personnel movement is analogous to the weekend effect, so such a variable may be useful for a variety of possible conditions.

4 Development of the Prototype CEPLOAD Expert System

Overview

CEPLOAD incorporates the load-forecasting model described in Chapter 3 to help boiler operators run heating plants at optimal efficiency. The operator inputs temperatures (forecasts and actual), and the expert system develops recommendations for allocating the heating load among available boilers. The program is intended to supplement the operator's expertise by taking much of the guesswork out of boiler load allocation.

Operation of CEPLOAD is outlined in the Appendix.

System Requirements

The boiler load application program requires a desktop microcomputer running a 386-class processor at 20 MHz with no less than 4Mb of random access memory (RAM). Microsoft Disk Operating System (MS–DOS) 5.0 and Microsoft Windows 3.1 are required, as is a VGA* card and display configured for 640x480 pixels. The computer's system clock must be current to correctly indicate the time for using the forecasted temperature data. The computer's hard drive must have room for MS–DOS, Windows 3.1, the boiler load expert system, the individual boiler load application programs, and their associated runtime modules.

Operating Environment

Windows 3.1 was selected as the program's operating environment primarily because of the better user interface and the greater capabilities of the development tools. Many applications are now available only for Windows, and those originally developed in the MS–DOS or other environments have been significantly enhanced for Windows.

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* VGA: video graphics adaptor.

The expert system selected was Kappa PC 2.1, a development environment that both USACERL and the contractor, the Institute of Gas Technology (IGT), are familiar with and have used in the past. It provides the basic operating program that accepts user input, defines boiler operating parameters, and evaluates facility status. Additional required programming was implemented with Visual Basic 2.0, another development environment familiar to the researchers.

A two-level programming approach was taken to handle the intensive calculations required to store and review the various possible boiler allocation combinations. Although Kappa PC is a capable environment, the fact that it is a list (string) processing program means certain sets of operations are not handled quickly or efficiently in comparison to others. For example, arrays can be simulated by lists of entries in multivalued variables, but accessing the fifth element in variable A is much slower than accessing A(5). The calculation for identifying the optimal combinations of boilers and boiler operating points took minutes on a 486/33 computer in the worst case (where as many combinations as possible were reviewed) after the various functions were optimized. Before optimization, the process was taking tens of minutes. Switching to the other language brought these calculations to seconds or tens of seconds to complete. This approach was required to help ensure that the calculations required for the forecast of a given hour are completed before the hour has passed.

Boiler Load Optimization Process

The goal of a boiler load allocation expert system is to define an optimum setting for each boiler to produce the required steam demands for a facility—the sum of each individual boiler output. The expert system will enable the end user (boiler operator) to define the boiler facility, and does not require a specific support person to perform setup. The boiler efficiency specification screen was set up to require boiler efficiency at operating points spaced at 10 percent increments of the boiler's rated capacity. The boiler performance entries were used directly rather than attempting to fit the entered points along a curve. In particular, this allows for boiler performance that has two or more relative peaks in efficiency.

A direct result of this approach is that determining the optimal combination of boiler operation and boiler loads—the greatest efficiency at the lowest overall cost—cannot be accomplished either by simple inspection or techniques such as linear programming. Linear programming requires that the constraints on independent parameters can be described by lines. Solutions are found by evaluating intersections of the various lines for optimum values. Solutions with even the simplest curves are inherently more complex.

The format of the data being entered by the user requires a different method to determine optimum points. The optimization process used in this work consists of exhaustive enumeration through the possible combinations of boilers and boiler efficiencies. For example, a two-boiler setup has a range of possible operating loads for each boiler, which allows the total to be equal to demand for the entire facility. To discover the optimal combination of the two, one boiler is iterated through its operating range. The second boiler delivery point, and the efficiencies for both, are then computed. The maximum combined (plant) efficiency, and the boiler load points that produced them, are found through the iteration.

The actual number of optimization points found depends on the operating mode of the boiler load allocation program. If the single-point mode is desired, the number of boilers used is the number of boilers that were indicated by the user as being on. The expert system's optimization module finds the point of maximum efficiency (or minimum cost) and returns it to the main routine. If the maximum capacity delivered by the boilers indicated to be on is insufficient for the load, or if the minimum capacity delivered by the boilers indicated to be on is over that of the facility load, the program notifies the user by displaying a message.

When the type of operation to be considered is the analysis based on forecasted information, the number of boiler and load-point combinations tried is based on the total number of available boilers. If the facility has five boilers, which is the most that CEPLOAD can accommodate, a total of 31 combinations (2^5-1) are compared to determine the best of the individual optimum values. This process is repeated for each hour of forecasted load required.

To determine the optimum combination that provides the best operation over an extended period, the individual boiler combination optimums are searched for the number of hours being considered. The efficiencies (or fuel costs) are accumulated across the hours, and the optimum load allocation is determined from these values. Once found, the values are returned to the main program.

Forecasting Loads

As implemented in the prototype expert system, the load forecast model consists of the calculations required using each forecast parameter coupled with the appropriate values from the historical log. Currently, this log consists of the previous facility loads, previous outdoor temperatures, load estimates for the previous 96 hours, and the current outdoor temperature. Using these values, the autoregression terms are calculated, and the forecasted load for the current hour is determined.

For projecting loads into the future to estimate the need for additional boiler capacity, the procedure uses the historical loads and the loads forecasted for the hour immediately before the hour being forecasted. For example, a forecast for a load 3 hours ahead uses the forecasted load 2 hours ahead with the coefficient for $FLOW_{-1}$, and the temperature forecasted 2 hours ahead with the coefficient for $TEMP_{-1}$. In this fashion, the load can be values.

One implication of this forecasting procedure is that, beyond a certain horizon, values are computed using forecasted rather than actual loads and temperatures. In addition, autoregression terms may become meaningless for forecast horizons beyond the subsequent period. For this reason, models that do not rely on autoregression terms (such as the models developed in this study) are expected to be more accurate for forecasting loads.

To accommodate the autoregression terms (if they are used), the forecast routines presume that the difference between forecasted loads and actual loads in the future is 0.

File Formats

The files used in the prototype boiler load allocation program serve three functions. The first is a record of the parameters used to specify facility configuration. This is done by using the SaveApplication() function within KappaPC, the expert system shell used to develop the prototype, which ensures that the basic definition is retained. The second function of the files is as an historical log of the temperatures, loads, and forecasted loads, which are used with the forecasting model to determine the expected loads. The third function is for communication between the two operating programs (KappaPC and Visual Basic). The specific files and their formats are described in the sections that follow.

BLR-CALC.DAT

The file containing the basic information that BLR-CALC.EXE uses is called BLR-CALC.DAT. It consists of the basic information for calculating forecasted loads (if desired) and determining the optimum boiler load allocation. It also contains the specifications for each boiler in the facility. This file is written by BLRALLOC.KAL and read by BLR-CALC.EXE.

BLR-CALC.DAT consists of the following lines:

1.   Number of hours to forecast loads, determined by the maximum of the number of hours required to turn on a boiler in the facility. This value is set to 0 for a run in manual mode, where the program determines the proper allocation for a predefined boiler setup.

2.   Load just experienced by the facility when forecasting values, or the current expected load for manual mode.

3.   Current outdoor temperature, which is used in forecasting loads.

4.   The number of boilers defined.

5.   Minimum boiler capacity, expressed in percentage of rated capacity, for first boiler.

6.   Rated capacity for first boiler, in 1000 lb/hr steam.

7.   Maximum boiler capacity, expressed in percentage of rated capacity, for first boiler.

8.   Efficiency of first boiler operating at 20 percent of rated capacity.

9.   Efficiency of first boiler operating at 30 percent of rated capacity.

10. Efficiency of first boiler operating at 40 percent of rated capacity.

11. Efficiency of first boiler operating at 50 percent of rated capacity.

12. Efficiency of first boiler operating at 60 percent of rated capacity.

13. Efficiency of first boiler operating at 70 percent of rated capacity.

14. Efficiency of first boiler operating at 80 percent of rated capacity.

15. Efficiency of first boiler operating at 90 percent of rated capacity.

16. Efficiency of first boiler operating at 100 percent of rated capacity.

17. Efficiency of first boiler operating at 110 percent of rated capacity.

18. Efficiency of first boiler operating at 120 percent of rated capacity.

19. Efficiency of first boiler operating at 130 percent of rated capacity.

Lines 5 through 19 are repeated for all boilers (up to five). If there is only one boiler, then a total of 19 lines are contained in BLR-CALC.DAT. For a five-boiler facility, a total of 79 lines are contained in BLR-CALC.DAT.

BLR-FCST.DAT

The forecast model coefficients for flow, temperature, autoregression, weekend (effect), and the constant are stored in the BLR-FCST.DAT file. It consists of one line per entry with the specific coefficients ordered in lag periods from most recent to least recent. The constant is at the end of the file. The coefficient groupings are ordered as follows: flow, temperature, autoregression, weekend, and constant. This ordering results in the following sequence:

$Flow_{01}$, $Flow_{02}$, $Flow_{03}$, $Flow_{04}$, $Flow_{06}$, $Flow_{12}$, $Flow_{24}$, $Flow_{48}$, $Flow_{72}$, $Flow_{96}$, $Temp_{00}$, $Temp_{01}$, $Temp_{02}$, $Temp_{03}$, $Temp_{04}$, $Temp_{06}$, $Temp_{12}$, $Temp_{24}$, $Temp_{48}$, $Temp_{72}$, $Temp_{96}$, $Auto_{01}$, $Auto_{02}$, $Auto_{03}$, $Auto_{04}$, $Auto_{06}$, $Auto_{12}$, $Auto_{24}$, $Auto_{48}$, $Auto_{72}$, $Auto_{96}$, $Weekend_{00}$, $Weekend_{01}$, $Weekend_{02}$, $Weekend_{03}$, $Weekend_{04}$, $Weekend_{06}$, $Weekend_{12}$, $Weekend_{24}$, $Weekend_{48}$, $Weekend_{72}$, $Weekend_{96}$, Constant

This file is written by BLRALLOC.KAL and read by BLR-CALC.EXE.

BLR-HIST.DAT

The BLR-HIST.DAT file contains the historical log of the previous 96 hours of data. It uses a comma-delimited, ASCII[*] format that consists of the last date-time of the previous forecast on the first line, and 97 lines containing the values of forecasted flow, actual flow, and temperatures from the previous 96 hours and the current values.

The date-time is formatted as

#YYYY-MM-DD HH:MM:SS#

with the time represented in 24-hour clock format. For example, 12 July 1993 at 11:17:23 a.m. would be written as #1993-07-12 11:17:23#.

Each hourly entry for forecasted flow, actual flow, and temperatures is separated by commas. For example, a forecasted flow of 123,000 lb of steam, an actual flow of 125,000 lb of steam, and a temperature of 29 °F would be stored as

123,125,29

---

[*] ASCII: American Standard Code for Information Interchange.

This file should be built using a suitable text editor. For purposes of setup, the actual and forecasted flows should be the same initially, with the program taking over recording of the updated values as it is running. This file is read and updated by BLR-CALC.EXE.

BLR-LOAD.DAT

The file BLR-LOAD.DAT contains a total of 72 forecasted flows, starting with the current hour. Each forecasted flow is written to its own line by BLR-CALC.EXE.

BLR-RSLT.DAT

The file containing the results of the boiler analysis is BLR-RSLT.DAT. This file is written by BLR-CALC.EXE and read by BLRALLOC.KAL. It consists of the following ASCII lines:

1.   Maximum efficiency/minimum operating cost for the operating point.

2.   The first boiler included in the combination, or 0 if no boiler fits.

3.   The percentage of rated load for the first boiler in the combination, or 0 if no boiler fits.

4.   The second boiler included in the combination, or 0 if only one boiler fits.

5.   The percentage of rated load for the second boiler in the combination, or 0 if only one boiler fits.

6.   The third boiler included in the combination, or 0 if only two boilers fit.

7.   The percentage of rated load for the third boiler in the combination, or 0 if only two boilers fit.

8.   The fourth boiler included in the combination, or 0 if only three boilers fit.

9.   The percentage of rated load for the fourth boiler in the combination, or 0 if only three boilers fit.

10.   The fifth boiler included in the combination, or 0 if only four boilers fit.

11.   The percentage of rated load for the fifth boiler in the combination, or 0 if only four boilers fit.

BLR-TEMP.DAT

The file containing the forecasted temperatures entered by the user through BLRALLOC.KAL is BLR-TEMP.DAT. It consists of the forecasted temperatures entered starting with Day 1 (now) at midnight, and proceeding through 11 p.m. on Day 4 (3 days later), for a total of 96 values. Each temperature is written as a numeric value on one line by BLRALLOC.KAL. The values are read by BLR-CALC.EXE. The program determines which value to actually begin using by looking at the system clock on the computer.

5 Conclusions and Recommendations

Different Facilities Need Different Models

This study has verified that an accurate forecast model can be developed for the prediction of boiler steam load. Using data from two facilities for multiple time periods, a series of dynamic regression models was developed. These models contained an unlagged temperature variable, a one-period lag of the dependent variable, and a constant term. In addition, other lags of the independent and dependent variable were specified, depending on the facility. The existence of different model terms for different facilities leads to the conclusion that one model type is not suitable for all facilities. Although the dynamic regression procedure is believed to be appropriate for steam load prediction at any facility, the terms and coefficients of the regression equation will vary significantly. It is recommended that a comprehensive forecasting effort be conducted for each facility. This requirement, however, is not severe because software packages are readily available for such purposes.

Historical Data and Model Accuracy

The accuracy of the forecast model is highly dependent on the historical data on which the forecast is based. For example, the suspect data from Fort Benjamin Harrison, discussed in Chapter 3, led to a reduced forecast confidence. This problem could be remedied by gathering more reliable data and refitting the forecast model. It is recommended that periodic "maintenance" be performed on a forecast model to verify its accuracy. Any significant facility modifications would be cause to refit the model. For example, the construction or closure of a large building on the base may affect steam consumption patterns.

Weather Forecasts and Model Accuracy

A reliable weather forecast is essential for the model to work correctly. The model requires an hourly temperature forecast to compute the predicted steam loads, which in turn affects the boiler load allocation algorithms. Although the model is "dynamic," and therefore capable of responding to changes in the dependent and independent data series,

the model's ability to adapt to changes in data is limited. Consistently inaccurate temperature forecasts will thwart the steam load predictions.

It is recommended that this model be applied primarily to 24-hour forecast periods, in recognition of the difficulty in obtaining consistently accurate hourly temperature forecasts for periods longer than 1 day into the future. However, the availability of improved temperature forecasts would allow the preparation of 48-hour, and even 72-hour steam load forecasts. The user is strongly advised to verify the accuracy of temperature forecasts being used in the boiler load allocation model. The program is written to automatically check on the temperature forecast errors (i.e., actual versus predicted temperatures) and report to the user if the forecasts are consistently erroneous. The user should monitor the system's accuracy statistic, and should switch to a different source for temperature predictions if the accuracy statistic is frequently violated.

Appendix: Operating CEPLOAD

Program Setup and Startup

Installation and operation of CEPLOAD requires the user to be familiar with basic Windows operations and file management functions. It is assumed that the reader is familiar with all basic Windows-related terminology (e.g., "click"). For more information on the operating environment, see the Microsoft Windows User's Guide.

To set up the files that make up CEPLOAD, establish a subdirectory on your computer's hard drive (e.g., c:\BOILALL). Copy the files to the subdirectory from the installation disk. Create a program group (window) using the windows file manager (optional), then create a program item (icon) for the program. (You may locate the program item in an existing window [e.g., Applications] if you prefer.)

Once installed, the program is started by a Windows command KAPPA-Runtime BLRALLOC.BIN, where KAPPA-Runtime is the appropriate name of the runtime module for KappaPC.

Another way to start the program is to start the KappaPC development environment, execute a File Open command with the BLRALLOC.KAL, then enter the command RunApplication() at the KAL Interpreter window.

General Operation

CEPLOAD's basic mode of operation is event-driven: it waits for input from the user before acting, and does not require ongoing input in any particular order. The basic functions are controlled through the main status display. Each type of operation is contained in its own screen. The screen displays are described in the following sections.

Main Screen

The boiler load allocation program uses the interface established by KappaPC through multiple screens. Upon starting the program, the primary screen is displayed. An example is shown in Figure A1.

In the upper-left quadrant of the screen, the data entry and related fields are displayed. The first field shows the last load experienced by the facility (if the forecast mode is to be used) or the current load to be distributed among the boilers. Placing the cursor within the box allows the user to update the value by typing the number. The next two fields show the date and time when the load field was updated, both of which change automatically when load is entered. These fields quickly allow the user to look at the screen and know when the load value was last updated. The fourth field in the upper-left quadrant shows the net efficiency of the facility in meeting the entire load as distributed across the boilers. This value is updated when the user executes the Evaluate command.

Figure A1. Boiler load allocation main screen.

The fifth field shows the current outdoor temperature. The user may update this value by placing the cursor in the box and typing the number.

The right half of the screen is dominated by rectangular fields showing the status of the boilers. A maximum of five rectangles are shown—one for each boiler defined for the facility. Each rectangle or boiler information display shows four information elements—one in each corner:

1.   The upper left element is the boiler identification, indicated by its number.

2.   The upper right element is the type of fuel specified for the boiler. The assignable values are COAL, GAS, and OIL. The value may be updated from the Availability screen (described below).

3.   The lower right element is the desired capacity setpoint for the boiler, expressed in thousands of pounds per hour. The value is updated when the user issues the Evaluate command.

4.   The lower left element is the boiler status. It can display one of five values: ON, OFF, STARTING, STANDBY, or UNAVAILABLE. The value may be updated by clicking on the button to the immediate left of the boiler information display. This displays a pop-up menu, in which the user indicates the boiler status by selecting the current mode. Pressing the button again removes the pop-up menu and returns the display to normal.

In addition to the change in description when a boiler's status is changed, the colors of the boiler information display also change to reflect the new mode. The ON mode is indicated by white text on a red background. The OFF mode is indicated by white text on a blue background. The STARTING mode is indicated by black text on a cyan background. The STANDBY mode is indicated by black text on a yellow background. The UNAVAILABLE mode is indicated by white text on a black background.

Below the boiler information displays is a checkbox for selecting and deselecting the manual mode of operation. If the checkbox is selected (checked with an "X"), the manual mode is selected when the Evaluate button is pressed. This prompts the program to allocate the existing load (entered at the top left corner of the screen) among the boilers indicated to be on. The manual mode allows the user to determine which combination of boilers will most effectively meet a given load. If the checkbox is deselected (empty), the program will execute a completely automated analysis, determining forecasted loads and the optimal combination of boilers and load points.

In the lower left quadrant of the main screen are control buttons that provide access to the other parts of the program. The function of each button is summarized below.

Evaluate—This button causes the program to write the necessary files and execute the subprogram for determining the optimum boiler combinations.

Availability—This button accesses the screen that allows the user to indicate the availability of staff, equipment, and fuel for a given boiler.

Forecast Model—This button accesses the screen that accepts user input pertaining to the forecast model coefficients determined by analysis of previous facility load data.

Exit—This button initiates shutdown of the expert system, exiting back to Windows. Before shutting down, the program writes the current information about the boiler facility back to the appropriate .KAL and .BIN files for later use.

Temp Forecast—This button accesses the series of screens for entering the temperatures forecast for the current and next 3 days.

Load Forecast—This button accesses the screen that will display the information about the forecasted facility loads. It is not functional in the prototype program, but will be in the full working version.

Cost Factors—This button accesses the screen that allows the user to enter the costs for each of the fuels (coal, gas, or oil) in dollars per million Btu (British thermal unit) energy input.

Boiler Definition—This button accesses the screen that allows the user to enter the operating parameters of the boilers in a facility.

The following sections describe the screens displayed by each button.

Temperature Forecast

The temperature forecast screens are displayed in sequence when the user presses the Temp Forecast button. An example is shown in Figure A2. The temperature forecast screens begin with the screen for the current day, with 24 fields for accepting entries corresponding to the hours from midnight (0000 hours) through 11 p.m. (2300 hours). Entries are made by using the mouse to point to a field, then clicking on it. The text

Figure A2. Temperature forecast screen.

cursor moves to that field, allowing the user to enter the forecasted temperature for that hour.

A button labeled Next is displayed in the lower right corner of the screen. Clicking on it advances the next day. The next screens are for Day 3, 0000–2300 and Day 4, 0000–2300. On the last day, the Next button changes to Go Main, which allows the user to complete the session of updating entries. On the second and subsequent screens, a Previous button appears, which allows the user to move back through the screens to the first (where the Previous button disappears).

Figure A3. Availability screen.

Availability

The Boiler and Resource Availability screen is displayed when the Availability button on the main screen is clicked, as shown in Figure A3.

The screen is arranged in columns and rows. Available boilers are listed along the left side of the screen. To the right of each boiler listing are fields for fuel type, staff availability, and materials availability. If a boiler can use more than one type of fuel, more than one fuel button is displayed (up to three). The Staff checkbox indicates whether staff is available to start a boiler. The Materials checkbox indicates whether all materials needed to start a boiler are on hand. If any materials are not available, the checkbox is deselected.

The Accept button at the lower right of the screen allows the user to indicate that the currently displayed status on boiler and resource availability is correct. Clicking Accept saves the settings and returns program control to the main screen.

Forecast Model

The Forecast Model Parameters screen is displayed when the Forecast Model button on the main screen is clicked. It is shown in Figure A4.

The model's parameters are displayed by category in columns as follows: Flow, Temperature, Autoregressive, Constant, and Weekend. Each parameter is also sorted by the lag term within rows, with the most recent time periods at the top. For example, the parameter associated with the fourth time period lag for temperature is found in the fifth row from the top in the second column. Fields for accepting values are only present when realistic. For example, there is no $Flow_0$ term because the model is for determining the

	Flow	Temperature	Auto Regressive	Constant	Weekend
0		-0.09404		6.52	0
-1	0.913717	0	0		0
-2	0	0	0		0
-3	0	0	0		0
-4	0.051614	0.034971	0		0
-6	0	0	0		0
-12	0	0	0		0
-24	0	0	0		0
-48	0	0	0		0
-72	0	0	0	Accept	0
-96	0	0	0		0

Figure A4. Forecast model screen.

steam flow in time period 0 (current time period). There are no constant terms other than constant because only one constant would be needed, if any.

Entries are made by using the mouse to point to a field, then clicking on it. The text cursor moves to that field, allowing the user to enter the forecasted temperature for that hour. The entries for each field should be either a number or 0—the latter meaning that the term did not have any appreciable meaning for the forecast model. Attempting to enter anything other than a number causes the program to display an error message and return to the prior value.

The button in the Constant column at the bottom of the screen is labeled Accept. Like the other Accept buttons, clicking it indicates that the user is satisfied with the parameters as displayed, and the program returns control to the main menu.

Boiler Definition

The Boiler Parameter Definition screen is accessed by clicking the Boiler Definition button on the main display. The user enters the characteristics of the facility's boilers on this screen, as shown in Figure A5. Assuming that a new installation is being defined, a hidden function resets the boiler definitions to the default of one boiler. The function is hidden and password-protected to ensure that the previously entered boiler definitions are not inadvertently cleared. Clicking with the right mouse button on the Accept button displays a small dialog box in the center of the screen, asking for a password. The password written into the program is "USACERL Reset", 13 characters total and case-sensitive. If anything but this is entered, the program returns to the Boiler Parameter Definition screen without clearing. If the password is accepted, a second dialog box displays two options: to continue resetting boiler parameters, or to abort and not reset them. Only after right-clicking on Accept, entering the proper password, and selecting the clear option are the boiler definitions reset.

Once reset, or when updating values, the topmost field is used for entering the description of the boiler (such as a location or manufacturer's name). As noted previously, the three fuel options are coal, gas, and oil. Clicking the checkboxes selects or deselects the fuel types, to indicate what the boiler is capable of burning. When a particular fuel type is selected, the Specify (Fuel) Firing Performance button can be clicked to display a column of input fields for boiler efficiency at various operating points. There is a field for entry of boiler efficiency at 10 percent increments, from 20 percent to 130 percent of the rated boiler capacity. Not all of the entries need to be filled, but any entries made must be contiguous and must span the minimum and maximum value range entered for the boiler. If the boiler's usable range ends in something other than an even 10 percent increment,

Figure A5. Boiler parameter definition screen.

the entry for the next lowest value must be calculated, to allow the program to interpolate the correct efficiency.

Clicking the Accept button closes the Firing Performance screen and returns control to the Boiler Parameter Definition screen.

The Nameplate Rating field, which is immediately below Fuel Options, pertains to the capacity of the boiler, expressed in thousand pounds of steam per hour. The rating is used as the reference point from which the other boiler operating points are determined. The minimum rating, full rating, and maximum rating overload, expressed in percentage of the nameplate rating, are entered in the next three fields. These values define the operating limits of the boiler. They must correspond to the boiler efficiency defined using the Specify (Fuel) Firing Performance button.

The next two fields are for entering the minimum amount of time required for the boiler to start cold and reach minimum steam flow, and to move from a cold start to full-rated output. The last two fields are for specifying the boiler's allowable ON/OFF cycles within a single year, and the number of ON/OFF cycles already completed.

Three control buttons are located at the lower right corner of the Boiler Parameter Definition screen. The Next Boiler button advances to the next higher numbered boiler; it is only displayed if there is a higher-numbered boiler to define. The Previous Boiler button moves the user to a lower-numbered boiler; it is displayed only if there is a lower-numbered boiler than the one displayed. The New Boiler button adds another entry for a new boiler, up to a maximum of five. For example, if a second boiler must be defined after having reset the configuration to one boiler, the New Boiler button is clicked to set up a second boiler form for entry.

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